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## The development of the error-related negativity (ERN) and its relationship with anxiety: Evidence from 8 to 13 year-olds

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### Abstract

Because anxiety disorders appear to follow developmental trajectories that begin early in development, it may be useful to examine the neurodevelopmental correlates of specific cognitive processes that have been linked to anxiety. For instance, the error-related negativity (ERN) is a negative deflection in the event-related potential that is maximal approximately 50 ms following the commission of errors at fronto-central electrode sites, and has consistently been found to be more negative among anxious adults. Much less, however, is known about anxiety and the ERN in children—especially when this relationship develops. We recorded event-related potentials (ERPs) while 55 children aged 8 to 13 performed an arrow version of the flankers task. Parents and children both reported on children's anxiety. Results suggest that the relationship between the ERN and anxiety changes as a function of age. Among older children, a larger (i.e., more negative) ERN was significantly related to increased anxiety based on parent report. Although the relationship was less robust, the relationship between ERN and anxiety was opposite among younger children. These results are discussed in terms of existing work on anxiety and the ERN, and the need for longitudinal and developmental studies on the relationship between ERN and anxiety.

### Keywords

ERN; error-related negativity; anxiety; children; adolescents; development

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Clinical anxiety appears to follow a developmental pathway beginning early in life. For instance, research suggests that infants who react negatively to novel stimuli tend to become toddlers who avoid new social experiences (Fox et al., 2005). Longitudinal studies imply continuity between adolescent and adult anxiety disorders (Birmaher et al., 1997) and early infant and childhood behavioral inhibition has been shown to predict the onset of clinically significant anxiety later in adolescence (Biederman et al., 2001; Chronis-Tuscano et al., 2009; Gladstone, Parker, Mitchell, Wilhelm, & Malhi, 2005; McDermott et al., 2009). Indeed, certain components of anxiety themselves may follow developmental transitions, such as fearful shyness expanding to include self-conscious shyness (Crozier & Burnham, 1990). Furthermore, shyness in middle childhood has been suggested to become increasingly associated with inhibition in the presence of others (Cheek, Carpentieri, Smith, Rierdan, & Koff, 1985) and with above normal self-concern (Buss, 1980). Although specific

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developmental pathways are not fully understood, anxiety disorders appear to follow developmental trajectories that begin relatively early in development (Pine, 2007).

Neural and cognitive development proceeds rapidly throughout middle childhood and into adolescence, and it may be possible to identify developmental changes in neural activity that relate to normative versus anxious trajectories of development (Casey, Tottenham, Liston, & Durston, 2005). In the context of this developmental cognitive neuroscience perspective, it may be fruitful to measure the neurodevelopment of specific cognitive processes that have been linked to anxiety disorders in adulthood (Pine, 2007). This approach could help identify developmental periods when measures of neural activity previously studied in adults begin to relate to individual differences in anxiety in children.

A growing body of research in adult anxiety disorders has focused on neural correlates of error detection reflected in the event-related potential (ERP). In particular, the error-related negativity (ERN) is an increased negative deflection occurring approximately 50 ms after the commission of errors compared to correct responses in speeded reaction time tasks (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993; Hajcak, Moser, Yeung, & Simons, 2005). The ERN reflects the activation of a generic error detection system that is evident across various stimulus and response modalities (Gehring, et al., 1993; van Veen & Carter, 2002).

Consistent with the view that anxiety may be associated with hyperactive error monitoring (McDermott, et al., 2009; Olvet & Hajcak, 2008), individuals with anxiety disorders are characterized by increased ERNs (Endrass, Klawohn, Schuster, & Kathmann, 2008; Gehring, Himle, & Nisenson, 2000; Hajcak, Moser, Holroyd, & Simons, 2007; Weinberg, Olvet, & Hajcak, 2010). Along similar lines, an increased ERN has been reported in relation to high trait anxiety and high levels of worry (Hajcak, McDonald, & Simons, 2003; Doreen Olvet & Greg Hajcak, 2009), but not to increased state levels of anxiety (Moser, Hajcak, & Simons, 2005).

Based on multiple studies that utilize source localization techniques (Dehaene, Posner, & Don, 1994; Mathalon, Whitfield, & Ford, 2003; van Veen & Carter, 2002), as well as work that combines ERP and fMRI (Debener et al., 2005), it is likely that the ERN is generated in the anterior cingulate cortex (ACC). Consistent with work on anxiety and the ERN, fMRI studies also suggest increased error-related ACC activity among anxious individuals (Fitzgerald et al., 2005; Paulus, Hozack, Frank, & Brown, 2002; Ursu, Stenger, Shear, Jones, & Cameron, 2003).

One fMRI study found that adolescents with generalized anxiety disorder showed greater activation in a network including the amygdala, ventral prefrontal cortex, and ACC in response to fearful faces (McClure et al., 2007). Similar to research findings in adults, some studies have reported increased ERNs among anxious children. The ERN is larger among children with obsessive compulsive disorder (Hajcak, Franklin, Foa, & Simons, 2008), children with non-clinical symptoms of obsessive-compulsive disorder (Santesso, Segalowitz, & Schmidt, 2006), and within a heterogeneous group of clinically anxious children (Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006). Consistent with the possibility that the ERN may relate to developmental processes of risk that emerge across development, one study found that behavioral inhibition (BI) assessed in early childhood predicted a larger ERN in adolescence (McDermott, et al., 2009). Moreover, ERN moderated the relationship between BI and the development of anxiety in adolescence: disorders were most common among those children who were high in BI and had a larger ERN. These data suggest that increased error-related brain activity may help delineate anxious versus non-anxious trajectories across development. However, existing studies have

focused on somewhat older children in their evaluation of the ERN and its relationship with anxiety (i.e., participants are often early adolescents), and no study to date has examined the relationship between ERN and anxiety as a function of age.

Neurodevelopmental studies suggest that the ACC matures into early adulthood (Cunningham, Bhattacharyya, & Benes, 2002) and that activation of the ACC increases over the course of development (Adleman et al., 2002; Van Bogaert, Wikler, Damhaut, Szliwowski, & Goldman, 1998). One neuroimaging study of 5 to 16 year old individuals found a significant correlation between volume of the right ACC and performance on a go/no-go task (Casey, Trainor, Giedd, et al., 1997). This same study found a significant correlation between age and volume of the right ACC, but not size of cerebrum. Consistent with these data, the ERN may not reach adult-like levels until the late teen years (Davies, Segalowitz, & Gavin, 2004). Davies and colleagues (2004) found that the amplitude of the ERN increased with age in a sample of 7 to 25 year-olds, with a significant age by gender interaction, which they suggested might reflect associations between pubertal onset and increases in the ERN. Another study found that ERN amplitude related to performance measures on a flankers task in adults but not in adolescents, suggesting that the relationship between ERN and behavioral measures emerges developmentally (Cecile D. Ladouceur, Dahl, & Carter, 2007). However, the ERN *can* be elicited among much younger children: one study found a robust ERN in children as young as 5 to 7 years old (Torpey, Hajcak, & Klein, 2009). In light of maturational changes that impact both the ACC and ERN, it may be important to examine the developmental relationship between ERN and anxiety as children transition from middle childhood to early adolescence—especially because this period marks a transition into a higher-risk period for anxiety and mood disorders (Costello, Egger, & Angold, 2005).

In addition to the ERN, the error positivity (Pe) is another component associated with response monitoring. The Pe appears within 200-500 ms following an error response, and appears to be independent of the ERN (Michael Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005; Santesso, et al., 2006). There is evidence that the Pe is affected by awareness of errors (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001), and may reflect a P300-like orienting response to errors (Ridderinkhof, Ramautar, & Wijnen, 2009). The Pe has not been consistently associated with anxiety disorders in adults or children, however (Endrass, et al., 2008; Hajcak, et al., 2008; Ladouceur, et al., 2006; McDermott, et al., 2009; Ruchow et al., 2005). Additionally, studies have suggested that the Pe is more invariant across development than the ERN, with Pe amplitudes in childhood matching those of adults (Davies, et al., 2004; Wiersma, van der Meere, & Roeyers, 2007).

In the current study, ERPs were recorded while 55 children aged 8 to 13 performed an arrow version of the flankers task (Eriksen & Eriksen, 1974). Both children and their parents reported on children's anxiety so that the relationship between anxiety and the ERN and Pe could be examined, as well as the impact of age on the association between anxiety and ERP measures. Based on previous work, we predicted that the ERN would increase with age in this sample, and that the relationship between ERN and anxiety would be moderated by age, such that the correlation between ERN and anxiety would be larger among older children. We did not expect the Pe to vary with age; in light of inconsistent findings on the Pe, we had no *a priori* hypotheses regarding its relationship with anxiety, or the moderating role of age on this association.

## Method

### Participant Recruitment and Screening

Subsequent to approval by the Stony Brook University Institutional Review Board, participants were recruited via a commercial mailing list targeting families with children between 8 and 13 years of age in Stony Brook and the surrounding community. Letters, followed by phone calls, went out to approximately 800 families from the mailing list. A total of 70 participants (30 female) between the ages of 8 and 13 participated in the study. Four participants were excluded from analysis due to poor quality recordings. Additionally, participants who committed errors on more than 25% of trials (i.e., 85 or more errors) and participants who committed fewer than 6 errors (Olvet & G Hajcak, 2009) were excluded from the final sample (11 subjects excluded in total). The final sample consisted of 55 participants (24 female). Behavioral data for one participant was lost as a result of experimenter error; therefore, behavioral results are based on 54 subjects (24 female). Assent was obtained from child participants and informed consent was obtained from their parent prior to the experiment. Participants received \$45.00 for their participation in the study.

The participants ranged from 8 to 13 years old and the mean age of the final sample was 10.95 (SD= 1.48); 89.1% of the sample was Caucasian, 1.8% was African-American, 1.8% was Asian, and 7.3% identified as Other.

### Self-Report

Two versions of the Screen for Child Anxiety Related Emotional Disorders (SCARED; Birmaher et al., 1997) were administered: one to the participants (Child-SCARED), and one to the parent who accompanied the child to the laboratory (Parent-SCARED). Both versions of the SCARED broadly assess symptoms of anxiety as they manifest in children, including symptoms of panic, general anxiety, separation anxiety, social phobia, and school phobia (Birmaher, et al., 1997). Each version consisted of a 38-item scale on which the participant can answer between 0 ('not true or hardly ever true') to 2 ('true or often true'); 1 corresponded to 'sometimes true'. The maximum score for each version is 76. Both versions also included 5 subscale scores: Panic/Somatic, General Anxiety, Separation Anxiety, Social Phobia, and School Phobia. Children filled out questionnaires either immediately before or after the EEG session; parents filled out measures during their child's EEG session.

### Task and Materials

An arrow version of the flanker task (Eriksen & Eriksen, 1974) was administered on a Pentium D class computer, using Presentation software (Neurobehavioral Systems, Inc., Albany, California, USA) to control the presentation and timing of all stimuli. Each stimulus was displayed on a 19 in (48.3 cm) monitor. On each trial, five horizontally aligned arrowheads were presented. Half of all trials were compatible ("<<<<<" or ">>>>>") and half were incompatible ("<<><<" or ">><>>"); the order of compatible and incompatible trials was random. Each set of arrowheads occupied approximately 1.3° of visual angle vertically and 9.2° horizontally. All stimuli were presented for 200 ms followed by an ITI that varied randomly from 2,300 to 2,800 ms.

### Procedure

After a brief description of the experiment, EEG electrodes were attached and the subject was given detailed task instructions. All participants performed multiple tasks during the experiment. The order of the tasks was counterbalanced across subjects and the results of other tasks will be reported elsewhere (see, e.g., Bress, Smith, Foti, & Hajcak, in prep). Participants were seated at a viewing distance of approximately 24 in (61 cm) and were

instructed to press the right mouse button if the center arrow was facing to the right and to press the left mouse button if the center arrow was facing to the left. Participants performed a practice block containing 30 trials during which they were instructed to be both as accurate and fast as possible. The actual task consisted of 11 blocks of 30 trials (330 trials total) with each block initiated by the participant. To encourage both fast and accurate responding, participants received feedback based on their performance at the end of each block. If performance was 75% correct or lower, the message “Please try to be more accurate” was displayed; performance above 90% correct was followed by “Please try to respond faster”; otherwise, the message “You’re doing a great job” was displayed.

### **Psychophysiological Recording, Data Reduction and Analysis**

Continuous EEG recordings were collected using an elastic cap and the ActiveTwo BioSemi system (BioSemi, Amsterdam, Netherlands). Thirty-four electrode sites were used, based on the 10/20 system, as well as two electrodes on the right and left mastoids. Electrooculogram (EOG) generated from eye movements and eyeblinks was recorded using four facial electrodes: horizontal eye movements were measured via two electrodes located approximately 1 cm outside the outer edge of the right and left eyes. Vertical eye movements and blinks were measured via two electrodes placed approximately 1 cm above and below the right eye. The EEG signal was pre-amplified at the electrode to improve the signal-to-noise ratio and amplified with a gain of one by a BioSemi ActiveTwo system (BioSemi, Amsterdam). The data were digitized at 24 bit resolution with a sampling rate of 1024 Hz using a low-pass fifth order sinc filter with a half-power cutoff of 204.8 Hz. Each active electrode was measured online with respect to a common mode sense (CMS) active electrode producing a monopolar (non-differential) channel. Offline, all data were referenced to the average of the left and right mastoids, and band-pass filtered between 0.1 and 30 Hz; eye-blink and ocular corrections were conducted per Gratton, Coles, and Donchin (1983).

A semi-automatic procedure was employed to detect and reject artifacts. The criteria applied were a voltage step of more than 50.0  $\mu\text{V}$  between sample points, a voltage difference of 300.0  $\mu\text{V}$  within a trial, and a maximum voltage difference of less than .50  $\mu\text{V}$  within 100 ms intervals. These intervals were rejected from individual channels in each trial. Visual inspection of the data was then conducted to detect and reject any remaining artifacts.

The EEG was segmented for each trial beginning 300 ms before response onset and continuing for 1,300 ms (i.e., 1,000 ms following the response); a 200 ms window from -300 to -100 ms before the response onset served as the baseline. Correct and error trials were averaged separately. For each subject, the most negative peak in a time window from 50 ms prior to response onset to 100 ms following the response was detected on error trials; the ERN was then quantified as the average activity in the 50 ms around this peak (i.e., 25 ms on either side of the peak) on error trials at a pooling of fronto-central sites (Fz, FCz, Cz, FC1, and FC2) where error-related brain activity was maximal. In addition, the correct response negativity (CRN) was evaluated in the same time window and pooling of electrodes on correct trials. Finally, the error positivity (Pe) was evaluated on error trials as the average activity at a pooling of Cz, CP1, CP2 and Pz from 200 to 400 ms following response onset. A comparable time window was also evaluated at the same sites on correct trials.

Behavioral measures included both the number of error trials for each subject, as well as accuracy expressed as a percentage of all valid trials. Average reaction times (RTs) on error and correct trials were also calculated separately, as were RTs on correct trials that followed correct and errors trials to evaluate post-error RT slowing. Trials were removed from all analyses if reaction times were faster than 200 ms or slower than 1,300 ms.



In examinations of the full sample, statistical analyses were conducted using SPSS (Version 17.0) General Linear Model software, with Greenhouse-Geisser correction applied to  $p$  values associated with multiple-df, repeated-measures comparisons when necessitated by violation of the assumption of sphericity.

The Pearson correlation coefficient ( $r$ ) was also used to examine associations between anxiety, behavioral and ERP measures. Because parent- and child-reported anxiety were only moderately related,  $r(54) = .35$ ,  $p < .01$ , behavioral and ERP measures were related to both child- and parent-reported anxiety separately. Hierarchical regression analyses were used to examine interaction effects.

## Results

### Self-Report

Overall, the mean score for the Child-SCARED was 18.00,  $SD = 10.17$ . The mean score for the Parent-SCARED was 10.00,  $SD = 7.14$ . The scores on each scale did not deviate from a normal distribution (Parent-SCARED/Child-SCARED kurtosis and skewness were .31/2.10 and .79/.89, respectively). In the Child-SCARED, the subscales were highly correlated with one another ( $r$ 's ranged from .55 to .82, all significant at  $p < .001$ ).<sup>1</sup> In the Parent-SCARED, the subscales were also highly correlated ( $r$ 's ranged from .49 to .78, all significant at  $p < .001$ ).<sup>2</sup> Additionally, children tended to skip more questions than their parents,  $t(1, 54) = 2.36$ ,  $p < .05$ .

### Behavioral Data

Overall, participants committed an average of 40.28 ( $SD=18.46$ ) errors, and were correct on 86.17% ( $SD=7.29$ ) of trials. Age was unrelated to accuracy,  $r(53) = -.17$ ,  $p = .21$ . Consistent with previous work, participants were faster on error,  $M= 371$  ms,  $SD= 66$ , than correct trials,  $M=517$  ms,  $SD= 105$ ;  $F(1, 53) = 148.60$ ,  $p < .001$ ;  $\eta_p^2 = .74$ . Older children were characterized by faster reaction times on both error,  $r(53) = -.34$ ,  $p < .05$  and correct,  $r(53) = -.56$ ,  $p < .01$ , trials. Participants were slower to generate a correct response on trials that occurred after an error,  $M= 525$  ms,  $SD= 107$ , than after a correct response,  $M=479$  ms,  $SD= 109$ ;  $F(1,53) = 36.74$ ,  $p < .001$ ;  $\eta_p^2 = .41$ ; moreover, the degree of post-error slowing (i.e., post-error RT minus post-correct RT) *decreased* with age,  $r(53) = -.30$ ,  $p < .03$ , and *increased* as a function of anxiety symptoms on the Child-SCARED,  $r(53) = .36$ ,  $p < .01$ . Accuracy was not related to Parent-SCARED or Child-SCARED,  $r(53) = -.10$ ,  $p = .47$ ;  $r(53) = -.02$ ,  $p = .87$ , respectively. Despite post-error increases in RT, accuracy was comparable after correct,  $M = 87.67\%$ ,  $SD= 6.32$ , and incorrect responses,  $M = 86.45\%$ ,  $SD = 10.87$ ,  $t(1,53) = .907$ ,  $p > .40$ . Parent's report of child anxiety was moderately correlated with post-error accuracy, such that increasing anxiety predicted worse post-error accuracy,  $r(53) = .26$ ,  $p < .06$ .

Correlational analyses were conducted to examine possible speed-accuracy trade-off effects. Partial correlations (controlling for age) were conducted between the percentage of errors and incorrect RTs,  $r(53) = .11$ ,  $p < .43$ , and correct RT,  $r(53) = .466$ ,  $p < .001$ . These results indicate that faster RTs were associated with reduced accuracy.

Overall then, errors were faster than correct trials, and there was evidence for post-error RT slowing, although accuracy was not improved following errors. Increasing age was

<sup>1</sup>Means and standard deviations for the Child-SCARED subscales: Somatic Panic,  $M = 1.29$ ,  $SD = .27$ , General Anxiety,  $M = 1.49$ ,  $SD = .40$ , Separation Anxiety,  $M = 1.55$ ,  $SD = .39$ , Social Phobia,  $M = 1.95$ ,  $SD = .54$ , School Phobia,  $M = 1.30$ ,  $SD = .34$ .

<sup>2</sup>Means and standard deviations for the Parent-SCARED subscales: Somatic Panic,  $M = 1.10$ ,  $SD = .17$ , General Anxiety,  $M = 1.40$ ,  $SD = .33$ , Separation Anxiety,  $M = 1.25$ ,  $SD = .27$ , Social Phobia,  $M = 1.61$ ,  $SD = .53$ , School Phobia,  $M = 1.17$ ,  $SD = .27$ .

associated with faster RTs and reduced post-error RT slowing. Moreover, post-error RT slowing was larger and post-error mistakes were more frequent among more anxious children.

### Error-related brain activity

Figure 1 (top; right) presents a topographic map depicting voltage differences (in  $\mu\text{V}$ ) across the scalp for error minus correct responses in the time window of the ERN. Grand average response-locked ERPs at the pooling of sites (i.e., Fz, FCz, Cz, FC1, and FC2) where the error minus correct difference was maximal are also presented in Figure 1 (top; left). Confirming the impression from Figure 1, the ERN was significantly more negative,  $M = -0.90 \mu\text{V}$ ,  $SD = 5.69$ , than the CRN,  $M = 2.81 \mu\text{V}$ ,  $SD = 4.78$ ;  $F(1,54) = 25.16$ ,  $p < .001$ ;  $\eta_p^2 = .32$ .

A similar topographic map used to depict voltage difference (in  $\mu\text{V}$ ) in the time window of the Pe is presented in Figure 1 (bottom; right), along with grand average response-locked ERPs at the pooling of sites (i.e., Cz, CP1, CP2 and Pz) where the difference between error and correct trials was maximal in the time range of the Pe (bottom; left). As suggested by Figure 1, the Pe was significantly more positive following error trials,  $M = 14.18 \mu\text{V}$ ,  $SD = 8.18$ , than following correct trials,  $M = 8.81$ ,  $SD = 5.37$ ;  $F(1,54) = 13.32$ ,  $p < .001$ ;  $\eta_p^2 = .21$ . Pe and ERN were uncorrelated ( $p > .65$ ).

### Correlations between ERPs and anxiety, and the moderating effect of age

In the full sample, none of the measures of anxiety (including the subscale scores) correlated with any ERP measures. Age was unrelated to the CRN and activity in the time-range of the Pe (on both error and correct trials); however, older children were characterized by a marginally larger (i.e., more negative) ERN,  $r(53) = -.24$ ,  $p < .10$ .

A series of hierarchical regression analyses were next conducted according to the procedures outlined by Aiken and West (1991) to examine the potential moderating effect of age on the relationship between anxiety and the ERN. Both child and parental report of child anxiety were included in these analyses. Age and both measures of anxiety were included in the model as independent variables, as were the two cross-products of age and each measure of anxiety (both centered). As indicated in Table 1, though child report of anxiety was not significantly associated with the magnitude of the ERN, age did have a moderating effect on the relationship between PSCARED and the ERN.<sup>3</sup> The interaction between age and Parent-SCARED was significant, as indicated by the product term having a significant unique effect,  $t(49) = 2.07$ ,  $p < .05$ , effect size (partial  $r$ ) = .28. Figure 2 (top) illustrates this pattern by showing the regression lines (based on the overall regression equation) for Parent-SCARED predicting ERN at one SD above and below the mean age of the sample. Among older children (i.e., one standard deviation above the mean age; 12.43 years), greater parental report of anxiety predicted a larger (i.e., more negative) ERN,  $r = -.35$ ,  $\beta = -.53$ ,  $t = 2.69$ ,  $p < .01$ , whereas in the younger children (i.e., one standard deviation below the mean age; 9.47 years) the relationship was positive and did not reach significance,  $r = .23$ ,  $\beta = .35$ ,  $t = 1.67$ ,  $p = .09$ .<sup>4</sup> At the mean age (10.95 years), there was no significant relationship between the magnitude of the ERN and parental report of anxiety  $r = -.06$ ,  $\beta = -.09$ ,  $t = .44$ ,  $p > .25$ . Analyses conducted with CRN activity did not reveal any significant relationships (all  $p$ 's  $> .4$ ).

<sup>3</sup>The same analyses were run using the factors of the Parent and Child SCARED. Of the factors, it appears that age has a moderating effect on the relationship between Factor 5 (School Phobia) and both ERN and Pe.

<sup>4</sup>The same pattern of results was found when congruent and incongruent trials were analyzed separately, though the Ns were reduced to 37 and 51, respectively, and the effects failed to reach significance.

For presentation purposes, a median split was conducted on the Parent-SCARED scores to create high- and low-anxiety groups among older (11 to 13 years old) and younger (8 to 10 years old) children. Figure 3 (right) presents topographic maps depicting voltage differences (in  $\mu\text{V}$ ) across the scalp for error minus correct responses in the time window of the ERN in each of these four groups. In addition, grand average response-locked ERPs for each group are also presented in Figure 3 (left).

The same analyses were repeated with the Pe on error trials; as noted in Table 1, the relationship between Parent-SCARED and the Pe also appeared to be moderated by the age of the child, such that a smaller Pe was associated with greater anxiety, but only among older children,  $r = -.45$ ,  $\beta = -.65$ ,  $t = 3.29$ ,  $p < .01$ . There was not a significant effect of anxiety on the Pe for younger children  $r = .14$ ,  $\beta = .27$ ,  $t = 1.00$ ,  $p > .10$ ; see figure 2, bottom. Similarly, at the mean age, there was not a significant relationship between the magnitude of the Pe and parental report of anxiety  $r = -.06$ ,  $\beta = -.19$ ,  $t = 1.15$ ,  $p > .10$ .

## Discussion

The results of the current study suggest that the relationship between the ERN and anxiety is moderated by age: only for older children in the current study, a larger (i.e., more negative) ERN was related to increased parent reports of child anxiety. Although the effect was not as robust in younger children, the observed relationship was opposite in direction: increasing parent-report of child anxiety was related to smaller (i.e., less negative) ERN.

Across the entire sample, ERN tended to be larger among older children at a trend level. These findings are broadly consistent with previous findings that the ERN fluctuates throughout development and begins to substantially increase around age 12 (Davies, et al., 2004). Event-related fMRI data also suggests that the ACC does not have a mature activation pattern until late adolescence (Crone, Zanolie, Van Leijenhorst, Westenberg, & Rombouts, 2008). Participants in the current study may have been too young overall to detect stronger robust age-related changes in the ERN that have been reported around age 13 (Segalowitz, Santesso, & Jeha, 2010).

Age was robustly related to RT measures in the current study: both RT and post-error RT slowing decreased among older children. Age was unrelated to performance accuracy, suggesting that as children got older, they were faster to respond and slowed less after errors but did not commit more errors (i.e., they performed better on the task). Child anxiety was related to both increased post-error RT slowing, and worse post-error accuracy. Thus, anxious children tended to slow down more following errors, but also perform worse after making a mistake. Post-error slowing is thought to be a behavioral adjustment to improve performance (Rabbitt, 1966) that results from the recruitment of cognitive control processes (Botvinick, Braver, Barch, Carter, & Cohen, 2001). The fact that anxious children slowed more after errors but also performed worse suggests that efficiency of ACC and prefrontal network functioning following an error might be compromised among anxious children. This is consistent with the assertion of attentional control theory that anxiety is associated with decreased processing efficiency, especially under stress (Eysenck, Derakshan, Santos, & Calvo, 2007).

In the current study, the ERN related to anxiety among 11 to 13 year olds—results that are consistent with existing data (Hajcak, et al., 2008; C. D. Ladouceur, et al., 2006; Santesso, et al., 2006) which have generally assessed somewhat older children (e.g., mean ages of 13.3, 10.2, 11.42, respectively). Because this relationship was not found among younger children, our data suggest that the relationship between increased error-related brain activity and anxiety may emerge in early adolescence. It has previously been suggested that pediatric



anxiety disorders are related to altered maturational patterns in ACC circuitry (C. D. Ladouceur, et al., 2006) and greater ACC activation in response to fearful faces (McClure, et al., 2007). Given that previous evidence indicates that the ERN does not reach adult-like levels until late adolescence (16-18 years old), it may be that there is a subset of anxious younger adolescents who begin to display adult-like ERNs and excessive error-related ACC activity. Excessive ACC activity may only begin to emerge as the ACC establishes some baseline of functional connectivity and adult-like structure.

It is also important to note that among younger children (i.e., 8-10 year olds), we found a weaker relationship between the magnitude of the ERN and anxiety that was in the *opposite* direction, such that higher child anxiety was related to a smaller (less negative) ERN. Collectively, these data indicate that the nature of the relationship between ERN and anxiety may fundamentally change across development—an unexpected finding that certainly warrants further study. One possible explanation for the changing relationship between anxiety and the ERN may be the differential development of the rostral and dorsal ACC. Specifically, one study found that the rostral ACC activity during response monitoring varied as a function of age, whereas dorsal ACC activation was only evident among adults (Velanova, Wheeler, & Luna, 2008). Thus, the ratio of dorsal to rostral ACC activity during response monitoring may increase across development. Considering that some studies have related anxiety to hypoactive rostral ACC activity in particular (Adleman, et al., 2002; Cunningham, et al., 2002), it is possible then that anxiety is related to hypoactive rostral ACC activity in both adults and children – and to increased dorsal ACC activity with increasing developmental changes. Future studies examining the relationship of childhood and adult anxiety to rostral and dorsal ACC activity in response to errors are needed to further investigate this possibility.

Alternatively, it is possible that the observed developmental change in the relationship between ERN and anxiety could relate to the changing phenomenology of anxiety across development. In particular, it is possible that younger children are more focused on external threat, whereas adolescents begin to monitor more for internal signals of danger. Work by Crozier suggests that children around age 5 display fearful shyness that expands to include self-conscious shyness by age 10 (Crozier & Burnham, 1990). In line with this, worry about behavioral competence and social evaluation increases with age (Spence, Rapee, McDonald, & Ingram, 2001; Vasey & Crnic, 1994). Given the strong relationship between the ERN and generalized anxiety disorder (Weinberg, et al., 2010) and pathological worry (Hajcak, et al., 2003), it is possible that ERN relates to more ‘cognitive’ forms of anxiety such as anxious apprehension, which may develop later than anxious arousal, or fear (Nitschke, Heller, Imig, McDonald, & Miller, 2001). Along these lines then, future research might examine the relationship between dimensions of anxiety and the ERN in a developmental context. It is possible that anxious arousal (i.e., fear) in younger children is related to smaller ERNs and anxious apprehension (i.e., worry) in older children is related to larger ERNs.

It is important to note that task difficulty could have played a role in the age group differences we observed in the ERN. A previous study found that ERN amplitudes were comparable between a group of adolescents and adults during a simple task, but adults showed larger ERNs during a more complex task (Hogan, Vargha-Khadem, Kirkham, & Baldeweg, 2005). Future studies might relate the ERN to developmental changes utilizing multiple tasks that vary in difficulty.

Consistent with previous findings (Davies, et al., 2004), we found no relationship between Pe amplitude and age. However, we did find that that age moderated the relationship between Pe and parent report of anxiety, such that among older children, higher levels of parent reported anxiety were related to a smaller Pe. This fits with evidence in some studies

that adults with high negative affect or anxiety have decreased Pe amplitudes, possibly due to do reduced error awareness (Gehring, et al., 2000; Hajcak, McDonald, & Simons, 2004; Hajcak & Simons, 2002). Thus, we found that in older children, the relationship between both Pe and ERN with anxiety was similar to that of adults. This is a novel finding in children and warrants further investigation.

It should also be noted that associations between anxiety and ERN/Pe in both the younger children and older children were found only when using parent report of anxiety. No significant associations were found using child reports. One possible reason for this discrepancy may be that children tended to skip more questions on the SCARED than their parents. Future work using both self-report and interview-based measures over multiple assessment points should be able to clarify whether an increased ERN/Pe is more related to parent or child reports of children's anxiety.

One other limitation that merits discussion is the possibility that other psychological conditions could have influenced the results. Specifically, ADHD has been implicated in impaired error monitoring (Crone, et al., 2008; Segalowitz & Dywan, 2009). It may be useful in future studies to examine the relationship between ERN/Pe and anxiety in children who have also been evaluated for other psychological conditions, and to utilize other measures of anxiety.

Further work in larger samples is necessary to better understand the developmental trajectory of the relation between ERN/Pe and anxiety. In particular, it will be important to track the development of the ERN/Pe and its relationship to anxiety within individuals across development, using longitudinal experimental designs. An intriguing possibility is that anxious young children with smaller ERNs may develop into anxious adolescents with larger ERNs. Insofar as the ERN has been proposed as a viable endophenotype for anxiety disorders (Olivet & Hajcak, 2008), the developmental relationship between anxiety and ERN will be important to characterize using longitudinal study designs.

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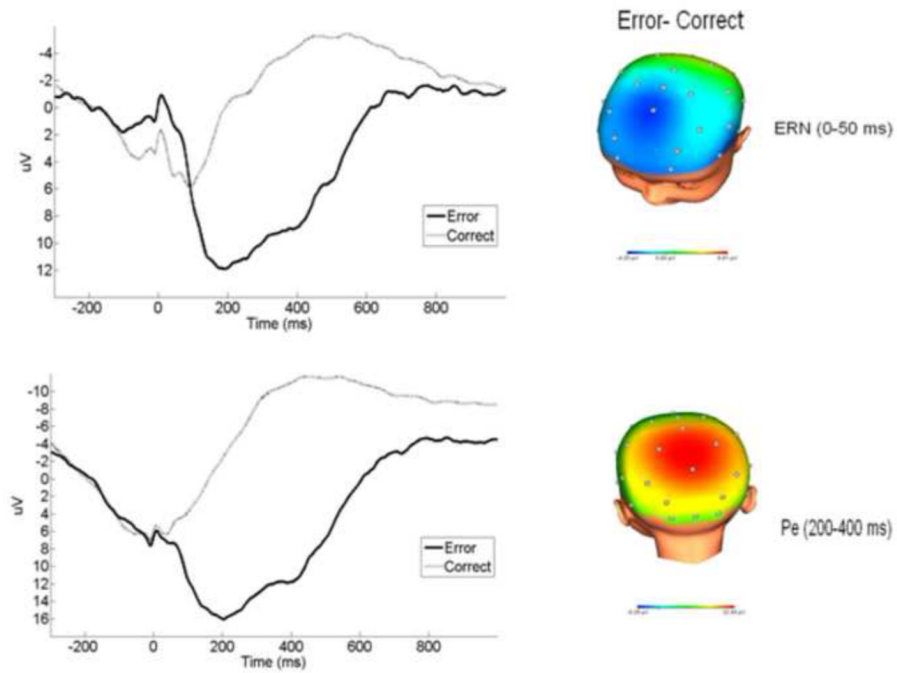
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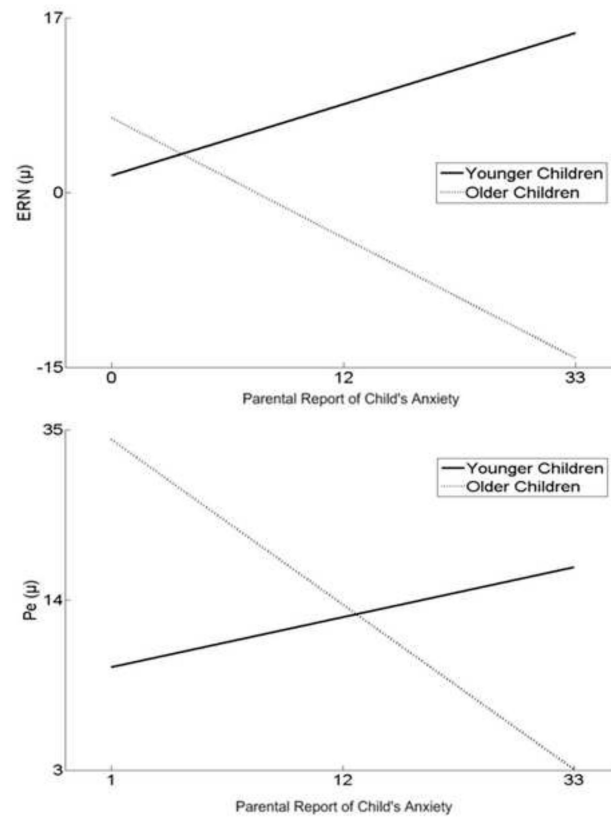


### Research Highlights

- Relationship between ERN and anxiety moderated by age in 55 children aged 8 to 13.
- Increased anxiety related to larger ERN among older children
- Increased anxiety related to a smaller ERN among younger children
- Opposite pattern of results for the error positivity (Pe)

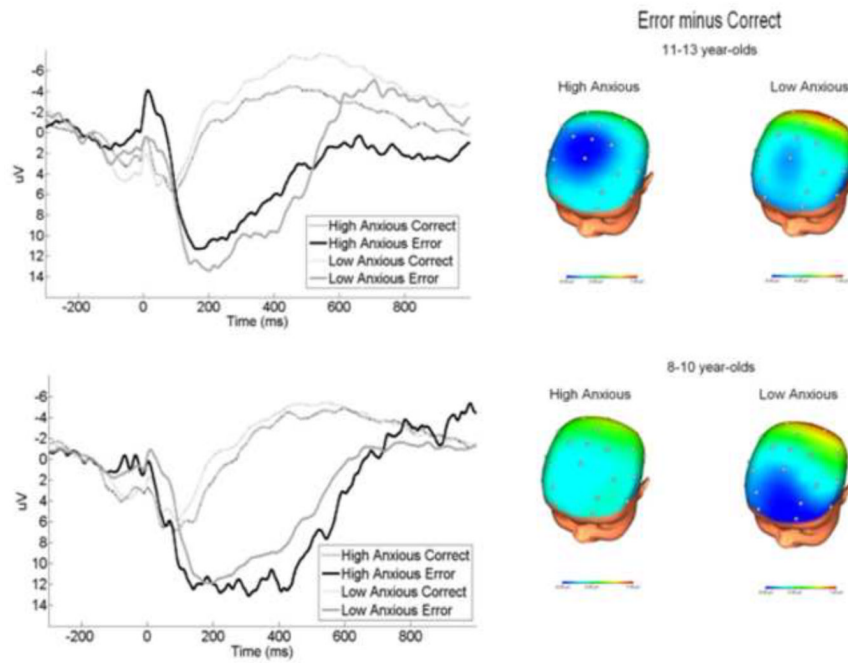


**Figure 1.** Response-locked ERP waveforms at Fz, FCz, Cz, FC1, and FC2 (top left), where the ERN was maximal. Below this are response-locked ERP waveforms at Cz, CP1, CP2 and Pz (bottom left), where the Pe is maximal. To the right are topographic maps depicting differences (in  $\mu\text{V}$ ) between error and correct responses in the time range of the ERN (0-50 ms; top) and the Pe (200-400 ms; bottom).



**Figure 2.**

The results of moderation analyses for the ERN (top) and Pe (bottom). Among older children a larger (i.e., more negative) ERN was associated with greater parental report of child anxiety (top); the opposite is true for younger children. A smaller (i.e., less positive) Pe was associated with greater parental report of child anxiety (bottom); again, this effect is reversed in younger children.



**Figure 3.** Response-locked ERP waveforms for participants high and low in anxiety based on parental report, among older (top) and younger (bottom) participants separately. Response-locked ERP waveforms (left) and topographic maps of activity in the time-range of the ERN (0-50 ms; right) for each of the four groups.

Results of hierarchical multiple regression examining the moderating effect of age on the relationship between Child Anxiety and the magnitude of the ERN.

**Table 1**

	ERN			Pe on error trials		
	$\beta$	$t$	$\beta$	$t$	$\beta$	$t$
Step One						
Child's age	-.25	1.79 <sup>†</sup>	.22			1.57
Child self-report of anxiety	-.05	.31	-.06			.39
Parental report of child anxiety	.04	.26	.08			.55
Step Two						
Child's age	-.29	2.10*	.17			1.27
Child self-report of anxiety	-.03	.21	.10			.68
Parental report of child anxiety	-.01	.04	-.10			.71
Age × Child self-report of anxiety	.03	.19	.14			.99
Age × Parental report of child anxiety	-.30	2.07*	-.31			2.13*

Note: for the ERN analyses,  $R^2$  for step 1=.06;  $R^2$  for step 2=.14; for the Pe analyses,  $R^2$  for step 1=.22;  $R^2$  for step 2=.36;

<sup>†</sup>  $p < .10$ ,

\*  $p < .05$ ,

\*\*  $p < .01$ ,

\*\*\*  $p < .001$